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YIELD PRESSURE MEASUREMENTS AND ANALYSIS FOR AUTOFRETTAGED CANNONS

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13. ABSTRACT *(Maximum 200 words)*

Yield pressure for a small permanent strain was measured in quasi-static laboratory tests of autofrettaged ASTM A723 steel cannon pressure vessels. Yield pressure was found to be a consistent ratio of the yield strength measured in close proximity to the area of observed yielding. Comparable yield pressure measurements for cannons firing with typical 5-ms pressure pulse duration gave 14% higher yield pressures, attributed to strain-rate effects on plastic deformation.

Calculated von Mises' yield pressure for the laboratory test conditions, including the Bauschinger-modified inner diameter residual stress and open-end vessel conditions, agreed with measured yield pressure within 3 to 5 %. Calculated yield pressure was found to be insensitive to the value of axial residual stress, since it is typically the intermediate value in the von Mises' yield criterion.

A description of yield pressure normalized by yield strength was given for autofrettaged A723 open-end pressure vessels over a range of wall ratio and degree of autofrettage, including effects of Bauschinger-modified residual stress. This method for calculating yield pressure is proposed as a design procedure for cannons and other pressure vessels.

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INTRODUCTION

Yielding of an autofrettaged thick cylinder, whether a cannon or some other type of pressure vessel, is a serious concern. Yielding of a vessel can affect function due to dimension change, it can decrease fatigue life due to loss of autofrettage residual stress, and yielding can be a safety hazard. Yield pressure is controlled by the applied and residual stresses in the vessel and by its material strength. The prudent user of a critical vessel should perform thorough stress analysis and material tests. However, accurate description of one control parameter for yielding of a thick cylinder–residual stress–can be elusive. Residual stress is difficult to measure, and calculated residual stresses can be affected by uncertainties in the analysis and input data, such as the nonideal Bauschinger yield properties of pressure vessel steels.

Recent work by Parker (ref 1) and Troiano et al. (ref 2) addresses some of the uncertainties of residual stress calculation for an autofrettaged cylinder. Methods have been developed that modify the familiar autofrettage residual stress distributions to account for Bauschinger-affected yield properties and the open-end loading condition that is appropriate for cannons and some other vessels. For the important inner diameter (ID) location of a vessel and for the ASTM A723 steel often used for high-pressure vessels, expressions are given (ref 2) for a useful range of diameter ratios and degree of autofrettage. These expressions are used here to calculate ID residual stress and the corresponding von Mises' yield pressure for comparison with measured yield pressure from cannon pressure vessels. Cannon sections with a range of yield strengths were quasi-statically pressurized in laboratory tests, and full-length cannons were pressurized by firing at a proving ground. Comparison of yield pressures from experiment and analysis will test the utility of Bauschinger-modified residual stress analysis for elastic strength design of pressure vessels.

ANALYSIS

Early empirical results are still useful for estimating the strains at the ID of an autofrettaged cylinder, in order to determine the degree of autofrettage in the comparisons here. Davidson and Kendall (ref 3) provided an expression for the total strain, ε_T, in the plastic region of an autofrettaged cylinder with inner, outer, and plastic radii, a, b, r_Y, respectively, as follows:

$$\varepsilon_T E_M/S_Y = 1.08(1-2v)LN(a/r_Y) + [r_Y^2(1-v) - b^2(1-2v) + (r_Y^2 b^2/a^2)(2-v)]/[3b^4 + r_Y^4]^{1/2} \qquad (1)$$

where E_M is elastic modulus (207,000 MPa), v is Poisson's ratio (0.3), and S_Y is yield strength of the cannons, listed in upcoming results. Figure 1 shows the configuration and some nomenclature. The approximate plastic radius for a given swage-autofrettaged cylinder can be determined by equating ε_T with the interference strain, ε_S, for a swage mandrel of radius, r_S, from the expression

$$\varepsilon_S = (r_S - a)/a \qquad (2)$$

Then the degree of autofrettage overstrain, n, is simply

$$n = (r_Y - a)/(b - a) \tag{3}$$

Equations (1) through (3) will be used to obtain the Bauschinger-modified hoop residual stresses at the tube ID for various values of n.

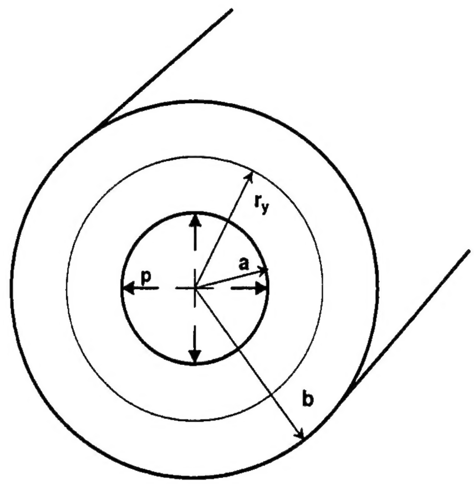

Figure 1. Pressure vessel configuration and some nomenclature.

The familiar Tresca plane-stress expressions for hoop residual stress in an autofrettaged tube were modified (refs 1,2) to apply to the von Mises' open-end conditions that are more appropriate for cannon pressure vessels and also to include the effect of the Bauschinger-reduced material compressive strength. The modified expressions for determining the hoop residual stress, S_{OE}, at the bore of an autofrettaged open-end tube of A723 steel are

$$S_{OE}/S_Y = \gamma R_S[(r_Y^2 - a^2) - 2b^2\,LN(r_Y/a)]/[b^2 - a^2] \tag{4}$$

where γ and R_S are the ratios that accomplish the modification for various tubes, and the remaining bracketed terms are the Tresca plane-stress expression for hoop residual stress. For A723 steel

$$\gamma = 1/[\{A(b/a) + B\}\,EXP[\{C(b/a) + D\}\,\{(r_Y/a) + E\}] + \{F(b/a) + G\}]$$

$$for\ r_Y/a > 1.5;\ \ b/a > 1.75) \tag{5}$$

and R_S for all steels is

$$R_S = 1.669 - 0.165(b/a) - 0.730n^3 + 1.984n^2 - 1.887n \tag{6}$$

The constants in equation (5) for A723 steel are:

- $A = 0.0816$
- $B = -0.0562$
- $C = 1.7519$
- $D = -7.4597$
- $E = -1.315$
- $F = -0.1077$
- $G = 1.216$

Additional details and results for other steels are in included in Reference 2.

Equations (4) through (6) are used here to calculate the hoop residual stresses at the ID of autofrettaged tubes, including the important effect of the Bauschinger-reduced strength for the type of steels used in cannons. Once the Bauschinger-modified hoop residual stresses are known, the Bauschinger-affected pressure, p_{VM}, at which the tube re-yields when subsequently pressurized can be determined, using the von Mises' criterion in the notation here

$$S_Y = [[(S_{\theta T} - p_{VM})^2 + (p_{VM} - S_{xR})^2 + (S_{xR} - S_{\theta T})^2]/2^{1/2}]^{1/2} \qquad (7)$$

where $S_{\theta T}$ is total hoop stress (sum of applied and residual) and S_{xR} is the axial residual stress. Effects of different formulations of axial residual stress on the resulting yield pressure are considered in upcoming results.

RESULTS FROM EXPERIMENT AND ANALYSIS

Measured Yield Pressure

Three breech-end sections of autofrettaged cannon tubes were used in laboratory tests in which pressure was applied in 15 MPa increments over the 600 to 850 MPa range. A press held the end load, creating open-end conditions. In separate tests, two cannons were fired with the firing pressure increased in similar increments over a similar range. In the laboratory tests, the permanent outer diameter (OD) hoop strain was measured at zero pressure after each increment. In the firing tests, the zero-pressure ID dimension was measured and the OD hoop strain was calculated from a correlation between OD strain and change in ID dimension established from laboratory tests. Plots of the OD strain for various applied pressures are shown in Figures 2 and 3. In all cases the permanent strain was measured in the chamber section of the cannon, with a = 79-mm and b = 148-mm. Following the pressurization tests, replicate hoop-orientation tensile tests were performed from material cut from the cannon chamber directly adjacent to the yielding location. The mean values of these yield strengths (0.2% offset), shown in Figures 2 and 3, give an accurate measure of material strength at the yielding location that is not affected by any variation of yield strength as a function of location in the cannon.

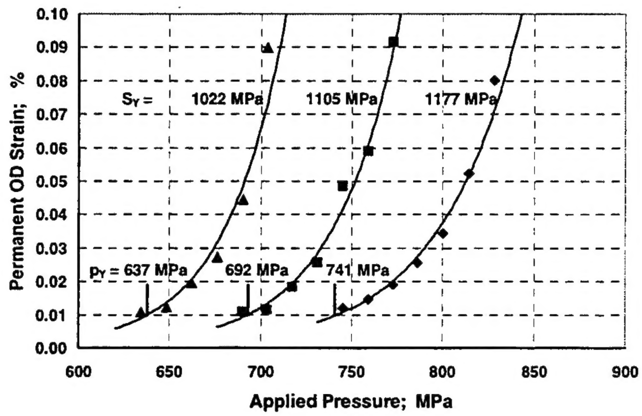

Figure 2. Laboratory overpressure tests of A723 steel cannon tubes; a = 79-mm, b = 148-mm.

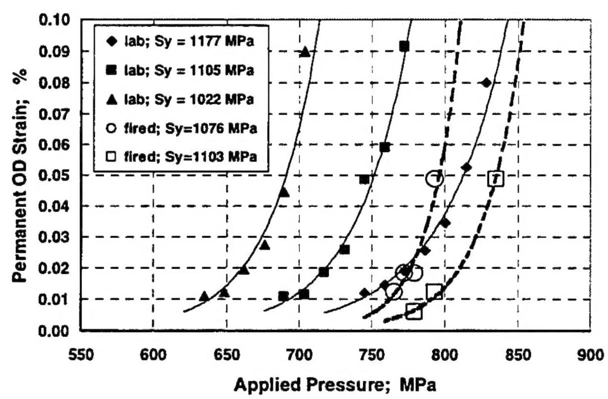

Figure 3. Laboratory and firing overpressure tests of A723 steel cannon tubes; a = 79-mm, b = 148-mm.

The laboratory OD strain versus pressure data shown in Figure 2 were fitted using an exponential expression from a spreadsheet in order to determine the pressure that produced 0.01% permanent OD hoop strain. This small value of OD strain corresponds to about one-third of the allowed variation in the OD dimension for a typical cannon tube. Values of this yield pressure at 0.01% strain, denoted p_Y, are listed in Figure 2 and Table 1 and compared with the yield strengths of the respective tubes. Note that p_Y is essentially constant with respect to material yield strength, as expected. This indicates that the overpressure and material strength tests were properly performed.

Table 1. Yield Pressure Measurements and Analysis

Strength S_Y, MPa	Measured Yield Pressure p_Y, MPA	p_Y/S_Y	Calculated Yield Pressure p_{VM}, MPa	p_Y/p_{VM}
1022	637	0.62	622	1.03
1105	692	0.63	666	1.04
1177	741	0.63	705	1.05

Calculated Yield Pressure

The calculated yield pressures listed in Table 1 were determined as outlined in equations (1) through (7), with the following inputs and procedures:

- The a and b in equations (1) through (3) were the autofrettage dimensions, 57 and 157-mm, respectively.
- The r_S in equation (2) was 58.4-mm.
- The a, b, and n in equations (4) through (6) were for the final chamber dimensions given earlier.
- The value assumed for the axial residual stress at the bore, S_{xR} , in equation (7) is zero.

The effect of other values of S_{xR} will be considered later. For these inputs, the calculated values of r_Y and n are listed in Table 2 for the laboratory tests and for two other arbitrary strength values (for later comparisons). The difference between n_{SWAGE} and n_{FINAL} is due to the difference between the autofrettage and final dimensions for the chamber region of the tube.

Table 2. Material Strength and Degree of Autofrettage

Yield Strength S_Y, MPa	Yield Radius r_Y, mm	Degree of Autofrettage n_{SWAGE}	n_{FINAL}
Laboratory Tests:			
1022	140	0.82	0.88
1105	134	0.76	0.79
1177	129	0.72	0.73
Calculations:			
1250	125	0.68	0.67
1350	120	0.63	0.60

The calculated von Mises' yield pressures, p_{VM}, are listed in Table 1 and compared with the measured yield pressures. Note the 3 to 5% agreement between measured and calculated yield pressure, with the measured pressure slightly higher as expected, since it results from a permanent strain as discussed earlier. This close agreement supports the assumption that $S_{xR} = 0$ in equation (7) is a reasonable choice for an open-end cannon pressure vessel.

Laboratory Versus Firing Pressurization

Comparison of overpressure test results under quasi-static laboratory and rapid loading firing conditions is shown in Figure 3. The laboratory results are the same as those in Figure 2, with total rise time from zero to peak pressure of about 10 seconds. The firing tests had a rise time of about 5 milliseconds, more than 10^3 faster, which raises the concern of time rate effects on the overpressure results. The yield strengths shown for the two fired tubes were determined as discussed earlier, with replicate tests taken directly from the location of observed yielding. Thus, the significantly higher pressure required for yielding of the fired tubes is attributed to time rate effects. Note particularly the pressure at 0.01% OD strain for the fired tube with $S_Y = 1103$ MPa, about 790 MPa, compared with the corresponding pressure for the laboratory tube with $S_Y = 1105$, about 690 MPa. This 14% higher yield pressure for the fired tube is attributed mainly to strain-rate effects causing delayed plastic deformation, rather than to an increase in yield strength. Kendall and Davidson (ref 4) measured about 3% increase in yield strength for a 10^3 increase in strain rate for a similar steel, whereas Dowling (ref 5) discusses 10% increases in ultimate tensile strength for metals due to delayed plastic creep for a 10^3 increase in rate. Thus, the increase in the effective yield pressure of a fired cannon is attributed primarily to delayed plastic deformation at the firing strain rate.

Effects on Calculated Yield Pressure

The importance of key inputs to calculated yield pressure of an autofrettaged thick cylinder is considered in the results of Figures 4 and 5. Figure 4 shows the results of different assumptions for values of the axial stress at the tube ID. The von Mises' yield pressure was calculated as described earlier, except using two alternative expressions for axial stress, in addition to the usual plane-stress open-end condition of $S_{R\text{-}x} = 0$. The other two are

$$S_{R\text{-}x} = \upsilon S_{R\text{-}\theta} \tag{10}$$

equating the axial residual stress to a (Poisson's ratio) portion of the hoop residual stress, as described by Parker (ref 1), and

$$S_x = S_{MAX} = p r_P^2/(b^2 - a^2) \tag{11}$$

where S_x is the maximum transient applied axial stress that can exist in a fired tube when a rapidly applied pressure, p, acts on the closed breech end of the tube with a radius r_P. Although it is unclear whether the 5-ms duration of firing pressure can produce enough transient axial stress to affect yielding, this upper-bound estimate of axial stress may have some utility.

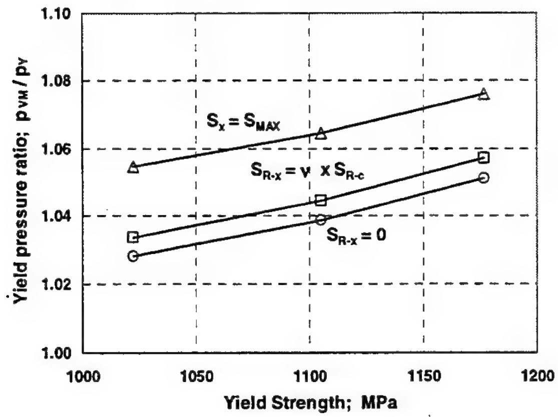

Figure 4. Effects of yield strength and longitudinal stress on yield pressure for cannon tubes; a = 79-mm, b = 148-mm.

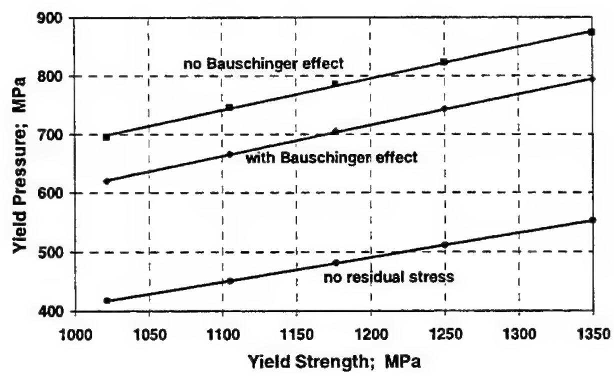

Figure 5. Bauschinger and strength effects on calculated yield pressure of cannon tubes; a = 79-mm, b = 148-mm.

The calculated yield pressure results for $S_{R-x} = 0$ in Figure 4, normalized by measured yield pressure, show the 3 to 5% agreement discussed earlier. For the $S_{R-x} = \upsilon S_{R-\theta}$ assumption, the result changes little, with 3 to 6% agreement between calculated and measured yield pressure. This can be explained by the fact that the axial stress is intermediate in value of the three stresses in the Mises' criterion and thus would be expected to have little effect on yielding. The yield pressure calculated from the upper-bound estimate of S_x can be seen to be 5 to 8% above the measured yield pressure. Considering this small effect and its low likelihood of occurrence and only for rapidly applied pressurization, it will be considered no further. All upcoming calculations of yield pressure will be for $S_{R-x} = 0$.

Figure 5 summarizes the important effects of autofrettage hoop residual stress on yield pressure, including the cases of no residual stress ($S_{OE} = 0$), residual stress with no Bauschinger effect ($\gamma R_S = 1$), and residual stress with Bauschinger effect (equations (1) through (7) as written). As expected, yield pressure with Bauschinger modified residual stress described here is considerably higher, by 44 to 49%, compared to that with no hoop residual stress. If hoop residual stress were used with no Bauschinger modification, still higher yield pressure would be

predicted, 10 to 12% above that with Bauschinger modification. However, use of yield pressure calculated with no Bauschinger modification is unwise. It appears that the nonideal, reduced compressive strength properties referred to as the Bauschinger effect are inevitably present in autofrettaged thick cylinders.

Yield Pressure Design

A review of equations (4) through (7) shows that a dimensionless ratio of yield pressure divided by material yield strength can be calculated as a function of two dimensionless variables, the wall ratio of the cylinder, b/a, and the degree of autofrettage, $n = (r_Y - a)/(b - a)$. Plots of this type would be useful for design, particularly so since they would include the important Bauschinger-modified ID hoop residual stress from recent work (refs 1,2). Figure 6 is such a plot, calculated as has been described and also including the measured yield pressures and yield strengths from the laboratory overpressure tests.

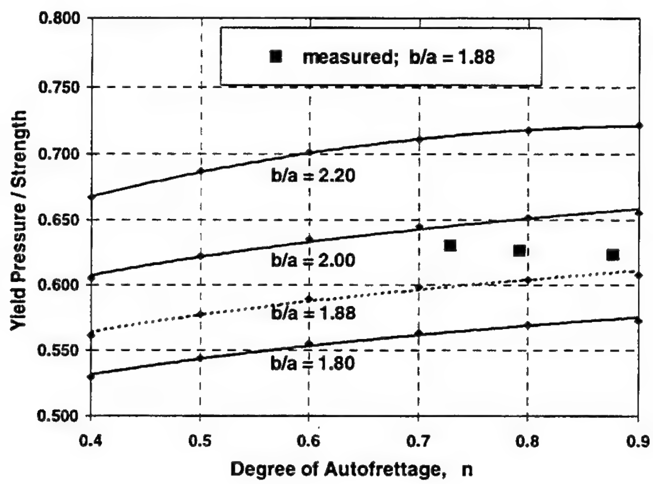

Figure 6. Yield pressure design curve for A723 steel pressure vessels with S_Y = 1000 to 1200 MPa.

First, note the diminishing return in yield pressure with increasing values of both n and b/a. For a series of equal increases in n or b/a, the corresponding increase in normalized yield pressure becomes progressively smaller. This has yield pressure design implications. Second, note that calculations were performed for b/a = 1.88, corresponding to the wall ratio of the laboratory tests. The measured p_Y and S_Y and the n for the laboratory tests (from Tables 1 and 2) were used to provide the direct comparison between measured and calculated yield pressure shown in the plot. The 3 to 5% agreement discussed earlier can be seen. It is proposed that the results of Figure 6 can be used for Bauschinger-modified yield pressure design of autofrettaged, thick, open-end cylinders made from A723 pressure vessel steel in the material strength range considered here, 1000 to 1200 MPa. Now that Bauschinger material property data are available for other steels used for pressure vessels (ref 2), the same type of yield pressure design information can be made available for these steels.

SUMMARY AND CLOSING

Measured yield pressure for a small permanent OD strain (0.01%) from quasi-static laboratory pressurization of autofrettaged A723 steel cannon pressure vessels was found to be a consistent ratio of yield strength measured at the yield location. Comparable yield pressure measurements, except for the rapid loading (5-ms pressure pulse) of cannon firing, gave 14% higher yield pressures, attributed to strain-rate effects delaying the plastic deformation.

Calculated von Mises' yield pressure for the laboratory test conditions and including Bauschinger-modified ID residual stress and open-end vessel conditions showed agreement with measured yield pressure within 3 to 5%. Calculated yield pressure was found to be insensitive to the value of axial residual stress, which has an intermediate value in the von Mises' yield criterion.

A general description of Bauschinger-modified yield pressure normalized by yield strength was given for autofrettaged A723 open-end pressure vessels over a range of wall ratios and degree of autofrettage. The calculated yield pressures are shown to agree well with the quasi-static yield pressure measurements from this work. This method for calculating yield pressure is proposed as a design procedure for cannons and other pressure vessels.

Closing Remarks

Two fundamental assumptions are implicit in the model calculations described here. Firstly that, when an autofrettaged cylinder is repressurized, the material behaves in an ideal linear-elastic, perfectly plastic fashion and secondly that the onset of further plasticity so predicted is associated with additional permanent plastic strain near the bore following depressurization. Given the convincing agreement with experimental evidence, these are likely subtle and second-order concerns. Nevertheless future work should include a more detailed numerical assessment of such potential interactions.

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